



# A review of surgical robots for spinal interventions

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## Abstract

**Background** This study aimed to describe the state of the art in surgical robotics for spinal interventions, a challenging problem for which robots can provide valuable assistance.

**Methods** Multiple electronic databases were searched for articles published during the last 10 years (2002–2012). Results were refined by defined inclusion criteria.

**Results** A total of 18 different robots were found. Among them, five are commercially available systems: one specifically designed for spinal surgery, one for percutaneous needle-based interventions, two are radiosurgical systems with reported applications on the spine and another is a commercial robot which has been experimentally tested on spinal surgery. The remaining projects are research prototypes which are still on validation stages.

**Conclusions** A comprehensive state of the art is presented, showing that spinal robotic surgery is still at an early stage of development but with great potential for improvement. Copyright © 2012 John Wiley & Sons, Ltd.

**Keywords** robot; spine; surgery; surgical robots; review; screw insertion; needle insertion

## Introduction

This article aims to describe the state of the art in robotics for spinal surgery, a demanding medical field for which robots already provide valuable assistance, although there is still plenty of room for improvement. Spinal surgery requires a very high level of precision, as it has considerable risks due to the critical structures that surround the spinal column: blood vessels are found close to the vertebrae and nerves connected to the whole human body are rooted to the spinal canal. Damage to any of these structures can produce considerable side-effects, ranging from pain to paralysis. These higher-than-normal requirements make robots ideal candidates for surgical assistants, as they can achieve superior levels of precision, are not affected by fatigue and can perform repetitive tasks without decreasing their performance.

The development of robots for spinal surgery dates back to 1992, although the largest part of the research effort is found during the last 10 years, i.e. 2002–2012, which is the period covered by this study.

Nowadays, robots are used for a variety of surgical procedures, such as transpedicular fixation. This type of surgery, which has attracted a lot of attention from robotic scientists, consists of the fixation of two or more vertebrae by means of screws inserted through the pedicles, which are later connected by metal bars. The screws and rods form a rigid structure which prevents relative motion between the vertebrae, hence preventing further damage to the one affected by fracture or herniation. Transpedicular fixation, apart from the dangers inherent

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to all spinal surgeries, has additional problems, such as possible pedicle fracture, difficult visualization of the surgical area and high exposure of the patient, surgeon and clinical staff to ionizing radiation if X-ray imaging is used to guide the intervention. All the aforementioned problems can be solved, or at least alleviated, by the use of surgical robotic assistants, which can help the surgeon to insert screws in precisely selected positions with minimal deviation.

Apart from transpedicular fixation, robots are now used for needle-based procedures, such as biopsies (1,2), vertebroplasties (3,4) and facet blocks (5). Robotic systems are also used for tumour ablation (6) and, to a lesser extent, for tumour resection (7). They also help to reduce radiation doses to surgeons, patients and clinical staff during interventions (8). Even more, ongoing research aims to develop robotized endoscopes capable of exploration and surgery in the sub-arachnoid space, which is only a few millimetres wide (9).

This article is divided into four sections: criteria for article inclusions are given in Methods, while chosen projects are described in Results; an analysis of the state of the art is given in Discussion, with final remarks in Conclusions.

## Methods

Publications about surgical robots for the spine were searched on the IEEE Xplore, PubMed, Google Scholar and CiteSeerX databases. On them, searches were performed for articles including the terms 'spine', 'vertebra' or 'pedicle', but always with accompanied by the word 'robot'. In addition, the Medical Robotics Database (MERODA) hosted by the University of Heidelberg<sup>1</sup> was searched for the same terms. Only the results which described mechatronic systems which performed clearly defined surgical tasks in an autonomous or semi-autonomous manner were included.

In particular, robotic systems designed for the following applications were discarded, as they fell out of the scope of this article:

- Simulators for surgical training.
- Testing of spinal specimens (e.g. load-bearing or kinematic analysis) helped by robots.
- General-purpose robots which, in theory, could be deployed in spinal surgery but without reports of actual experiments.
- Robotic systems which only performed image acquisition tasks (e.g. cone-based computed tomography).

## Results

Applying the methods described in the previous section, a total of 18 robotic projects were found, which are summarized in Table 1. Descriptions of them are given in the

<sup>1</sup><http://www.umm.uni-heidelberg.de/apps/ortho/meroda/robdat.php>

following sections, citing the applications for which they were designed, their main technological features and a summary of their performance results.

## Early systems (before 2002)

The earliest work on robotic-assisted spine surgery was traced back to 1992 and was reported by a research team from Grenoble, France (10). As in many other early studies on surgical robotics, the authors adapted an industrial robot, in this case a PUMA 260, for use in the operating room. The robot was designed as an assistant for transpedicular fixation, holding a laser guide which pointed drilling trajectories over the patient's vertebrae. Surgical planning was carried out on a segmented pre-operative computed tomography (CT) scan, which was registered to intra-operative X-ray images. The authors presented a drilling experiment on plastic vertebrae, on which they claimed to obtain sub-millimetre accuracy.

In 1995, Santos-Munné *et al.* (11) proposed another robotic system for transpedicular fixation, which shared many similarities with the project first presented in Grenoble: it also advocated the use of an industrial robot (a PUMA 560), intra-operative X-ray imaging system and planning of drilling trajectories on pre-operative CT scans. Differing from previous work, the proposed system placed a drill guide on the robot's end-effector, which was made of radiolucent material with embedded metal spheres. In this way, it could be located on the intra-operative X-ray images and registered to the coordinates of the planned trajectories. The authors neither reported about the project's implementation nor gave experimental results.

Some years later, researchers from the Fraunhofer Institute developed the Evolution 1 surgical robot, which was commercialized by Universal Robot Systems (URS) and deployed on multiple clinical institutions. Although Evolution 1 was designed for neurosurgery, a research effort was made to extend its use to spinal interventions under the project named 'Robots and Manipulators for Medical Applications' or RoMed (12). However, URS went out of business some time later, forcing its former clients to stop using their robot, due to the cessation of maintenance and technical support (13).

## Robots for screw insertion

The majority of robotics projects developed between 2002 and 2012 – more precisely 8 out of 18 – have focused on screw insertion, a task required for surgeries such as transpedicular fixation and cervical body fusion. Detailed descriptions of these robots are given in the following sections and a summary of the most relevant experiments using them can be found in Table 2.

### *SpineAssist/Renaissance*

A major breakthrough for spinal robotic surgery came in 2003, when a team of Israeli researchers presented the Miniature Robot for Surgical procedures, or MARS (14).

Table 1. Summary of the main applications, features and references of the studied robotic systems

Name (or main reference)	Applications	Commercial availability	Operation modes*	Dof	Tracking technology	References
SpineAssist	Transpedicular fixation, vertebroplasty, biopsy, GO-LIF	Yes (FDA clearance and CE mark)	Assistive	6	Fluoroscopy	(8,14–20)
SPINEBOT v 1	Transpedicular fixation	No	Assistive, autonomous	7	IR tracking	(21)
CoRA	Transpedicular fixation	No	Assistive, tele-operated	6	IR tracking	(22)
SPINEBOT v 2	Transpedicular fixation	No	Assistive	5	Bi-planar fluoroscopy	(23)
VectorBot/Kinemedic	Transpedicular fixation	No	Assistive	7	IR tracking	(24,25)
Neuroglide (Wang2010)	Cervical interbody fusion	No	Assistive	4	IR tracking	(26)
MINOSC	Laminectomy	No	Autonomous	2	Force sensing	(31)
	Sub-arachnoid space exploration, localized electro-stimulation	No	Tele-operated	5	Endoscope	(9)
AcuBot	Vertebroplasty, biopsy, nerve blocks	Yes (FDA clearance)	Assistive, tele-operated	6	Fluoroscopy, intra-operative CT	(1,5)
Innomotion	Biopsy	Paused (CE mark)**	Tele-operated	5	Intra-operative MR, intra-operative CT	(2)
DLR LWRIII	Biopsy, vertebroplasty	No***	Assistive, tele-operated	7	IR tracking, 3D radiography	(3)
Cyberknife, Novalis da Vinci	Tumour ablation	Yes (FDA and CE mark)	Autonomous	6	Fluoroscopy	(6,43–47)
RIME (Onogi2005)	Tumour resection	No	Tele-operated	7 (for each arm)	Endoscope	(7,40–42)
SpineNav	Transpedicular fixation	No	Tele-operated	6	IR tracking	(27,28)
RS55	Vertebroplasty	No	Autonomous	5	Fluoroscopy, IR tracking	(4,36)
	Vertebroplasty	No	Autonomous, tele-operated	5	Intra-operative CT	(37,38)
	Transpedicular fixation	No	Assistive	5	IR tracking	(29,30)

\* Assistive, the robot acts as a mere assistant, keeping the surgical tools in place while the surgeon manually performs the actual drilling or insertion; Autonomous, the robot is capable of drilling or instrument insertion by itself, without direct intervention of the surgeon; Tele-operated, the robot replicates the surgeon's motion, although the latter controls it remotely from a console.

\*\*The Innomotion commercialization was stopped in 2010, although it is expected to be restarted in 2012.

\*\*\*The system proposed by Tovar-Arriaga (3) is a research prototype, although it is based on the LWR robot commercialized by KUKA.

Table 2. Summary of experiments for robots designed for screw insertion

Robot	Brief description	Evaluation criteria	Results	Operated segments	References
SpineAssist	Insertions of 32 guide wires and four screws on six cadavers. Accuracy checked using post-operative CT scans	Implants' measured deviations in all planes (sagittal, coronal and axial) with respect to the surgical plan are < 1.5 mm	32 of 36 implants correctly inserted (88.89%)	L1–L5 and S1	(18)
SpineAssist	Retrospective study of 3912 screws and guide wires inserted on patients operated in 14 institutions, June 2005–June 2009	Surgeons' judgement if post-operative CT scans were unavailable. Otherwise, screws were considered correctly inserted if, at most, breaches of < 2 mm were observed	Without CT: 3204 of 3271 screws correctly inserted (98%). With CT: 635 of 646 screws correctly inserted (98.3%)	Unavailable	(19)
SpineAssist	Retrospective study of 112 patients, 55 operated using SpineAssist and 57 with a conventional protocol	Screw completely contained within pedicle or, at most, encroaching the cortical bone region	94.5 % using SpineAssist. 91.5% using conventional protocol	Unspecified segments on thoracic, lumbar and sacral regions	(8)
Spinebot v 1	Target following experiment, tracking a moving target which emulated the patient's breathing Drilling of a moving plastic phantom, using the robot as tool holder, and then by completely autonomous drilling	Measurement of error by means of an optical tracking system	Deviation bounded by $\pm 1.5$ mm with a maximum of 0.45 mm	None	(21)
Spinebot v 2	Insertion of screws on 14 spinal levels of two cadavers	Error measured as distance between planned and actual perforation points using a post-operative CT scan	Observed error in the 1–2 mm range for both cases	None	(23)
VectorBot	Machining experiments on artificial bone and a bovine spine, observing the influence of various parameters, such as tool choice, drilling speed, controller gains, entry angles and optical tracker sampling rate. No screws were inserted	Screws completely contained within bones with no breaches. Axial and lateral angles measured using a post-operative CT scan Measurement of deviation errors between planned and actual entry points. Measurement of force profiles	26 of 28 screws correctly inserted (92.86%) Axial deviation of $2.45 \pm 2.56^\circ$ . Lateral deviation of $0.71 \pm 0.21^\circ$	T11–T12, L1–L5	(25)
Neuroglide	Screw insertion on the cervical sections of six cadavers	Post-operative CT scans measuring the translational and angular errors of inserted screws	Milling better than drilling in terms of forces and accuracy. Reactive forces always < 15N. Mean deviation for milling of 0.42 mm with a maximum of 1.7 mm. High speeds (30 000 rpm) and sampling rates (20 Hz) increase accuracy. High proportional and integral gains reduce pose errors and settling time while increasing the robot's stiffness 8 of 10 screws correctly inserted (80%) with mean translational and angular errors of 1.94 mm and $4.35^\circ$ *	C1–C2	(26)

\*Robot's parameters were tuned during experiments, so not all insertions were performed under the same conditions. Mean values are not representative. Brief descriptions of the experiments are given, as well as the used criteria for analysis. Summary of results are given, with special emphasis on proportion of successfully inserted implants (i.e. screws or guide wires) and their observed deviations

MARS evolved into the SpineAssist, now commercialized by Mazor Robotics (Cesarea, Israel), which is still the only robot available in the market, with FDA and CE clearances, specifically designed for spinal interventions, such as biopsies, transpedicular fixation, scoliotic back correction and vertebroplasty. To this date, SpineAssist has been validated by 2500 procedures worldwide, on which over 15,000 implants have been placed without reported cases of nerve damage (15). Recently, Mazor Robotics introduced the Renaissance, a new version of SpineAssist, which, despite keeping its core technologies, had a complete overhaul in its software and user interface. It also added new features, such as the C-OnSite, which permits the acquisition of 3D images using a normal C-arm, by manually rotating it around the patient. The Renaissance is also expanding its clinical field beyond the thoracic and lumbar spine: it has successfully been used for brain biopsies and in the world's first robot-assisted surgery on the cervical spine.<sup>2</sup>

MARS/SpineAssist was designed as an intelligent tool holder for interventions that required percutaneous insertions of needles and screws. Its main innovation was its reduced size and weight, which permitted its direct attachment to the patient's bony structure. This greatly simplifies the registration on pre- and intra-operative images, as neither tracking nor immobilization are needed, as no relative motion between the patient and the robot is possible.

The MARS prototype was a high-precision parallel manipulator with six degrees of freedom (DoFs), which had a cylindrical shape (base  $25\text{ cm}^2 \times$  height 7 cm), a weight of 200 g, positioning errors of  $< 0.1\text{ mm}$  and could stand forces up to 10 N (14). The team behind MARS advocated the use of small robots, as they occupy less space in the operating room. This, however, reduces their working volume and makes them less able to withstand reactive forces, which, in the case of drilling, can reach 15 N. Although small robots are considered safer, as they are less able to damage clinical staff in the case of a malfunction, it must be noted that even small forces exerted on nerves or blood vessels can severely damage the patient.

SpineAssist, shown in Figure 1, is an improved version of MARS, slightly bigger (base diameter 5 cm  $\times$  height 8 cm, 250 g weight) and complemented with different mounting platforms. For minimally invasive interventions, SpineAssist can be used with the Hover-T, also shown in Figure 1, which is a plastic railing anchored on two points of the patient's pelvis and one of the spinous process of an upper vertebra. For open procedures, the robot can be mounted directly over the spine, using a clamp and bridge. In addition, two different bed-mounted platforms are available for biopsies, cervical interventions and guided oblique lumbar interbody fusion procedures, which are described later. It must be noted that SpineAssist suffers from its limited working space, so it may not be able to reach a required position during intervention, so additional extensions must be attached to the mounting platforms to solve this problem (16–18).

<sup>2</sup>[http://ryortho.com/spine.php?news=1898\\_First-RobotGuided-Cervical-Spine-Surgery](http://ryortho.com/spine.php?news=1898_First-RobotGuided-Cervical-Spine-Surgery)

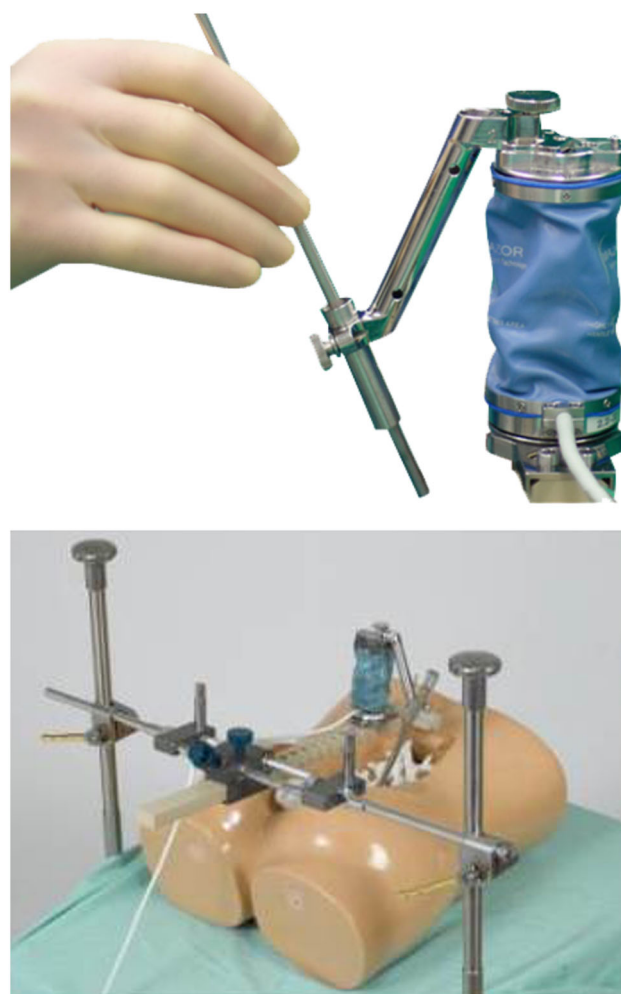


Figure 1. (Top) SpineAssist robot with an instrument guide. (Bottom) SpineAssist mounted over the Hover-T system. Reprinted with permission from Mazor Robotics. Copyright © Mazor Robotics Inc.

The surgical workflow with SpineAssist consists of five steps: (a) planning of the optimal positions and dimensions of implants, based on pre-operative CT scans; (b) attachment of the needed mounting platform to the patient's bony anatomy; (c) acquisition of two X-ray images, which are automatically registered to the CT scan; (d) mounting of the robot on the platform, which latter aligns its arm with the planned screw (or tool) trajectory; and (e) drilling through the guiding tube held by the robot's arm, followed by the insertion of the guide wire and screw. Robot motion, drilling and insertion are repeated for all required implants.

After attainment of FDA clearance, SpineAssist has been used by clinical teams worldwide, mostly in Israel, Germany and the USA, which have reported their experiences in multiple peer-reviewed publications. In 2007, Togawa *et al.* (18) published the results of a cadaveric study using SpineAssist for insertion of pedicle and translaminar facet screws. For the first type of surgery, 32 guide wires and four pedicle screws were inserted into six cadavers, evaluating the implants' accuracy by post-operative CT scans. The results revealed that 32 of the 36 placements (88.89%) were within  $\pm 1.5\text{ mm}$  of the planned positions, with an overall deviation of  $0.87 \pm 0.63\text{ mm}$ . In 2010, Devito *et al.*

(19) published a retrospective study about the use of SpineAssist between June 2005 and June 2009 on 14 different hospitals worldwide, analysing a total of 842 patients. Intra-operative fluoroscopy was used to assess 3271 screws and guide wires inserted in 635 patients, of which 3204 (98%) were found to be correctly placed. In 139 cases, more detailed quantitative analyses using post-operative CT scans were made, which revealed that 635 of 646 implants (98.3%) were correctly inserted, with 577 (89.3%) being completely contained within the pedicle and 58 (9%) showing breaches of < 2 mm. No cases of permanent nerve damage were observed and 49% of the interventions were made percutaneously, a considerably higher rate than the common 5% rate using non-robotic approaches cited by the authors. In 2011, Kantelhardt *et al.* (8) published a retrospective study in which 55 patients underwent pedicle screw placement surgeries using SpineAssist and 57 were operated following a conventional protocol. The authors found that patients in the first group had a significant increase in the proportion of screws placed with no breaches (94.5% vs 91.4%), reduced times of X-ray exposure per screw (34 s vs 77 s) and better recoveries after the interventions. In addition to the articles cited here, Mazor Robotics' website hosts an extensive list of publications about SpineAssist, which should be consulted by interested readers.<sup>3</sup>

SpineAssist has also enabled a new type of surgery, called guided oblique lumbar interbody fusion (GO-LIF), which consists of the fixation of two vertebrae by insertion of two screws from the inferior vertebra to the superior one, crossing the intermediate inter-body disc space. In this way, only two screws are needed for fixation instead of the typical four and the connecting rods. This type of surgery is inapplicable by conventional free-hand techniques, due to the high level of precision it requires. A recent preclinical study on cadavers has demonstrated its feasibility, with an error level of  $1.3 \pm 0.2$  mm with respect to the pre-operative plan (20).

#### SPINEBOT, SPINEBOT v 2 and CoRA

Three different surgical robots have been presented by Korean researchers, all of them designed for transpedicular fixation. In 2005 a team from Hanyang University presented the SPINEBOT, a robot capable of automatic drilling, a feature missing from previously existing projects for this intervention (21). SPINEBOT used in-house planning software and an optical tracking system based on spherical reflective markers for localization of the surgical tools and patient. In 2009, a team from the Pohang University of Science and Technology (POSTECH) used SPINEBOT's planning and tracking system with a different robot, called the cooperative robotic assistant (CoRA), a more robust prototype capable of automated screw insertion and haptic feedback (22). In 2010, a cadaveric study was reported using a completely redesigned SPINEBOT (which will be named 'SPINEBOT v 2'), with fewer DoFs and without the automatic drilling capabilities (23).

As mentioned in the previous paragraph, the original SPINEBOT project comprised not only the surgical robot but also planning software and an optical tracking system. The proposed software, named HexaView, allowed the surgeons to plan the screw insertions using six different views of a CT or magnetic resonance (MR) scan of the patient. The optical tracking system was commercialized by NDI (Waterloo, Ontario, Canada) and offered feedback at 30 Hz for redundant position control of the robot, in addition to its embedded encoders. The robot, as shown on Figure 2, consisted of a Cartesian positioner, a gimbal and a tool holder, which provided three, two and two DoFs, respectively, giving seven DoFs in total. The robot was able to do the gross and fine positioning of the surgical tools and keep them in place while the surgeon carried out the drilling, although it was capable of doing this task autonomously if desired. SPINEBOT also included a motion-correction system, a remarkable feature missing from earlier projects, which was based on the optical feedback and could correct the patient's motion produced by breathing, which had an amplitude of 3 mm in the antero-posterior direction according to the authors (21).

Chung *et al.* (21) reported multiple experiments using SPINEBOT. In one, they made the robot follow a moving target, which performed a sinusoidal motion with an amplitude of 2 mm and a period of 5 s, emulating a breathing patient. SPINEBOT was able to follow the target with an error bounded by  $\pm 0.15$  mm and a maximum of 0.45 mm, values close to the 0.35 mm error introduced by the optical tracking system. In a second experiment, holes were drilled in a moving plastic phantom, first by a person who used the SPINEBOT as a tool holder and then by the robot working in fully autonomous mode. In both cases, observed deviations were in the 1–2 mm range, although the robot's accuracy seemed slightly superior.

Lee *et al.* (22) used the SPINEBOT's planning and tracking systems with the improved robot CoRA, a sophisticated device capable of automated drilling and screw insertion, a feature which, according to the authors, was implemented for the first time. The robot, as shown in Figure 3, was built with a more robust frame, which permitted it to withstand larger reaction forces but hindered the surgeon's access to the patient. In addition, CoRA offered cooperative control, a tele-operated drilling system with realistic haptic feedback and a small and lightweight end-effector. Lee *et al.* published some proof-of-concept experiments in their article, but did not provide a quantitative analysis of CoRA's performance. As the planning and tracking systems were identical to SPINEBOT's, the authors expected CoRA to have similar levels of error in screw placement (1–2 mm) as the main source of inaccuracies, -that is, the optical system- remained unchanged. At the time of writing this paper, no further experiments on phantoms or cadavers using CoRA have been published.

The SPINEBOT v 2, presented in 2010, was completely different from the first SPINEBOT, despite keeping the same name. As can be seen in Figure 4, the new robot had only five DoFs – one prismatic and four rotational joints – and, more importantly, it lacked the automated

<sup>3</sup><http://www.mazorrobotics.com/int/physicians-int/peer-review-library-int.html>

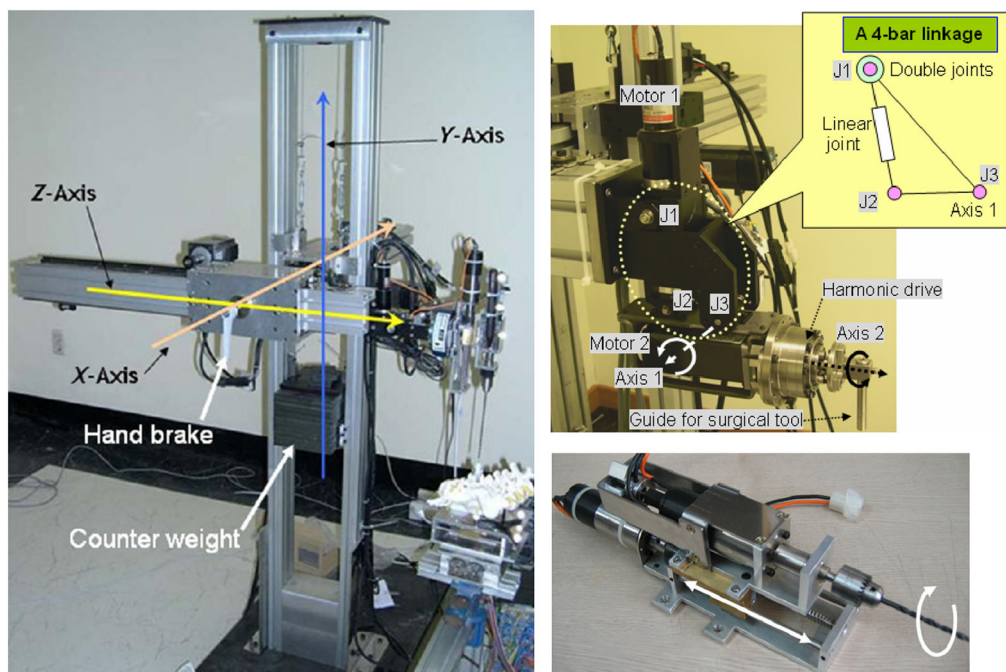


Figure 2. The first version of SPINEBOT described (21): (left) the whole system, showing the three DoFs of the Cartesian mechanism; (top right) close-up of the gimbal which provides two DoFs and holds the tool guide; (bottom right) close-up of the linear tool guide, with its additional two DoFs. Reprinted with permission from Centre for Intelligent Surgery Systems, Hanyang University. Copyright © Centre for Intelligent Surgery Systems, Hanyang University

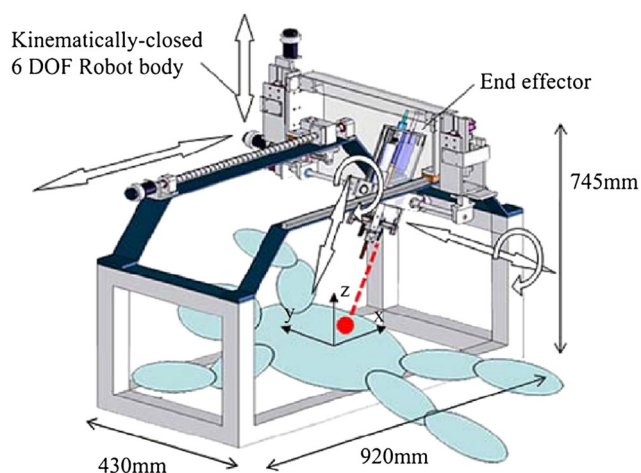


Figure 3. Schematic of the CoRA proposed by Lee *et al.* (22), with its dimensions and DoFs. Reprinted with permission from Haptics and Virtual Reality Laboratory, Pohang University of Science and Technology (POSTECH). Copyright © Haptics and Virtual Reality Laboratory, Pohang University of Science and Technology (POSTECH)

drilling capabilities, replacing the original end-effector by a simpler tool holder. Its planning software also went through a complete redesign and the tracking system was replaced by biplanar continuous fluoroscopy. Instead of relying on optical tracking, SPINEBOT v 2 detected the patient's and tool positions by processing the fluoroscopic images – updated at 20 Hz – and by means of custom 2D–3D registration algorithms (23).

The authors performed laboratory experiments to estimate the overall positioning error of SPINEBOT v 2, which was found to be  $1.38 \pm 0.21$  mm. On the cadaveric tests, 28 screws were inserted in 14 different vertebrae of two

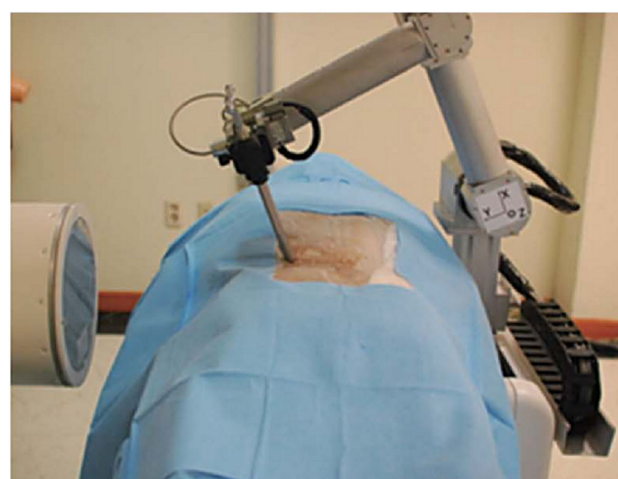


Figure 4. SPINEBOT v 2, as described (23). The treadmill at bottom right corresponds to the robot's prismatic joint. Reprinted with permission from Centre for Intelligent Surgery Systems, Hanyang University. Copyright © Centre for Intelligent Surgery Systems, Hanyang University

cadavers and post-operative CT scans were made to assess the screws' insertions and measure their angular deviations. Of the 28 total screws, 26 were correctly positioned (success rate of 92.86%), with no observed perforations into the spinal canal. Average angular errors were  $2.45 \pm 2.56^\circ$  and  $0.71 \pm 1.21^\circ$  in the axial and lateral planes, respectively (23).

#### VectorBot/Kinemedic

The Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre, DLR) has developed a series of light-weight robots designed for multiple surgical scenarios, giving a desirable degree of versatility that could compensate

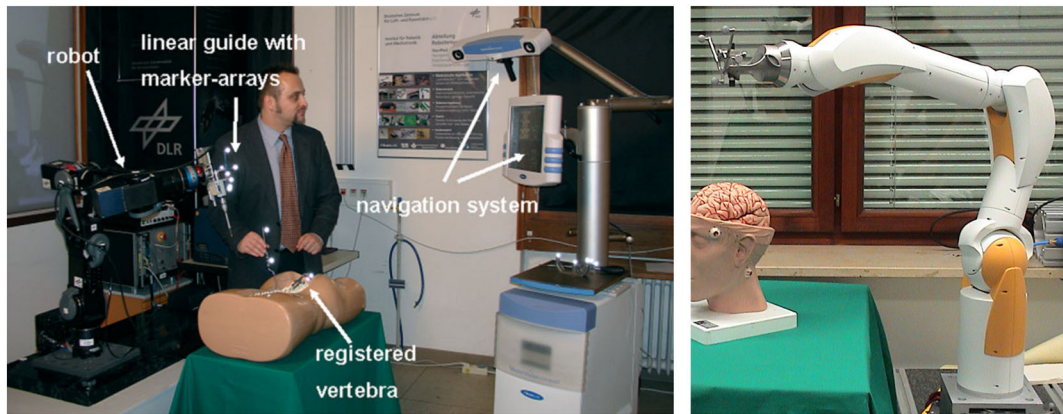


Figure 5. The DLR's surgical systems: (left) the prototype using the LWR II, coupled with the navigation system and reflective markers; (right) Kinematic robot, successor of the LWR II. Left figure reproduced from (25). Reprinted with permission from John Wiley and Sons. Copyright © 2006 John Wiley and Sons Ltd; right figure, Reprinted with permission from Institute of Robotics and Mechatronics. Copyright © Institute of Robotics and Mechatronics, DLR

the increasing cost and complexity of medical robotic systems. DLR's research has also covered spinal surgery, specifically transpedicular fixation, as described in publications by Ortmaier *et al.* (24,25). This project was given the name 'VectorBot' by BrainLab (Feldkirchen, Germany), who sponsored it with a \$5 million investment but, unfortunately, cancelled it before its introduction to the market (13).

The VectorBot consisted of the DLR's Kinematic robot coupled with the VectorVision optical tracking system developed by BrainLab, although early prototypes were developed using the preceding Light-weight Robot II (LWR II). Both robots are shown in Figure 5. The VectorBot required no X-ray images, as all the tracking was made using markers attached to the patient's vertebrae and points collected by the optical system. Thus, radiation was reduced to a minimum but at a cost of increased invasiveness, due to the large incisions required to expose the spine. In line with other research projects, the authors preferred a robot that worked as an assistant, providing help to the surgeon rather than executing the intervention autonomously. This assistance came in the form of virtual fixtures, i.e. physical limits imposed by the robot, which prevented the surgeon from deviating too much from the planned trajectories. The robot was not capable of automatic drilling or screwing, although it kept the surgical instrument in a safe and stable location while the surgeon remained in control of these tasks.

In 2006, Ortmaier *et al.* (25) published the results of a series of evaluation experiments with their proposed system. In them, the authors carried out two different machining tasks, drilling and milling, on a block of artificial bone and a bovine spine, measuring hole diameters, pose errors and reactive forces for different machining tools, entrance angles and values of control parameters. Summarizing their results, they concluded that milling was superior to drilling in terms of deviation errors and reactive forces, due to the larger slippage of the drill tip observed during drilling, which bent the instrument and increased friction inside its guide. Mean deviation error for milling in the plane perpendicular to the instrument axis was of 0.42 mm, with the maximum reaching up to 1.7 mm.

Maximum forces reached up to 15 N, well below the limit of 30 N which could be handled by the robot. In terms of control parameters, the authors concluded that the optimum was reached with high proportional and integral gains, which led to higher robot stiffness, lower pose errors, reduced settling time and decreased overshoot. The authors identified the accuracy and latency of the optical tracking system as critical factors. However, they acknowledged that additional sources of error in the system were not taken in account in their study, such as pre-operative image resolution, segmentation accuracy and intra-operative registration errors.

#### Neuroglide

The majority of robots for screw insertion were designed to operate in the lumbar section. This has technical advantages – lumbar pedicles are larger than thoracic and cervical ones, so precision requirements are less demanding – but also clinical relevance, as fusions in the lumbar area are more common than those carried out in other spinal regions. This has reduced interest in interventions at the cervical level, a problem addressed by Kostrzewski *et al.* (26), who proposed the Neuroglide<sup>4</sup> robot for cervical interbody fusion in 2012. The proposed system was designed specifically for atlanto-axial fusion, i.e. the fusion of the upper two vertebrae, C1 and C2, by means of screws inserted through both of them.

The Neuroglide consisted of a high-precision, parallel, four-DoF mechanism that held a drill guide, as shown in Figure 6. The robot's reduced size limited its workspace, but gross positioning was carried out by means of a passive serial arm on which the robot was mounted, also shown in Figure 6. Navigation was implemented using an infra-red optical tracker and active markers attached to the robot and vertebrae, previously exposed by an incision and registered to the pre-operative space by probing points on the bony surface. The authors also developed a custom

<sup>4</sup>Kostrzewski *et al.*'s publication does not cite the robot's name, which was taken from the project's website (<http://lsro.epfl.ch/vrai/projects/Neuroglide>)



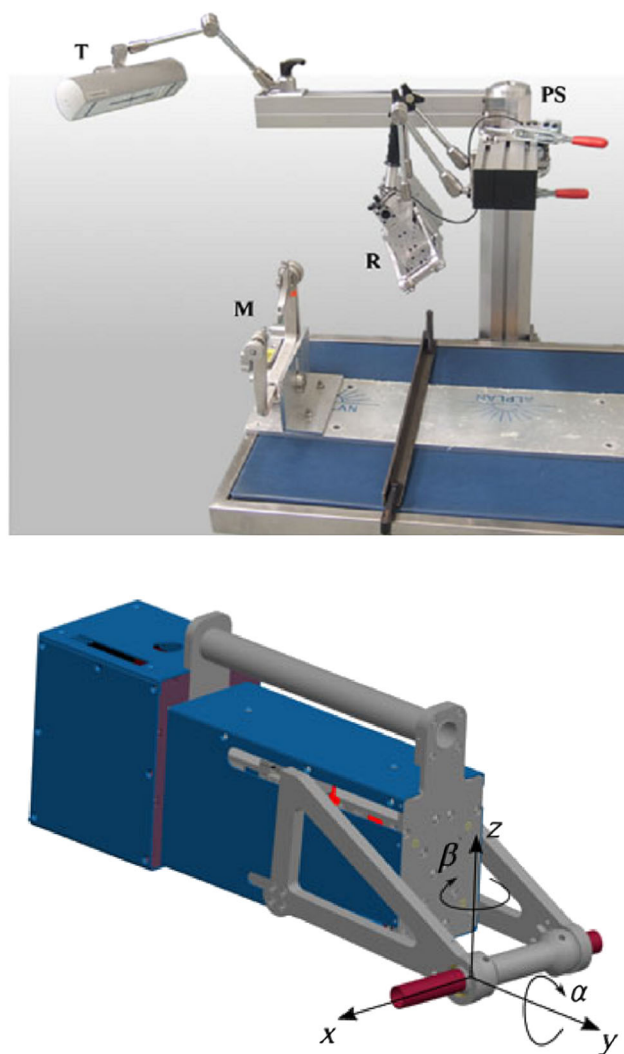


Figure 6. Neuroglide robot for cervical surgery: (top) aspect of the complete system with the robot (R), passive mounting structure (PS), optical tracker (T) and Mayfield clamp (M) for skull attachment; (bottom) illustration of the robot with the drill holder coloured in red. Robot's DoFs are along the  $y$  and  $z$  axes and around angles  $\alpha$  and  $\beta$ . Figures reproduced from (26). Reprinted with permission from John Wiley and Sons. Copyright © 2011 John Wiley and Sons Ltd

joystick for robot control and software for navigation and surgical planning, which was used to determine the screw trajectories based on pre-operative CT scans.

The Neuroglide was evaluated in a feasibility experiment with six cadavers, in which an experienced neurosurgeon inserted a total of 10 screws, fusing the C1 and C2 vertebrae, and then evaluated the insertions with post-operative CT scans. The mean translational error reported by the authors was 1.94 mm and the mean rotational error was  $4.35^\circ$ , although two screws were dropped from the statistical sample, due to their abnormally large errors produced by drill slippage. It must be noted that the authors improved multiple aspects of their system while the experiments were under way, so results are not comparable directly, as they were not obtained under the same conditions. Furthermore, the sample size was not large enough to draw meaningful conclusions. However, the authors reported a remarkable result after all their improvements

were in place (0.41 mm and  $2.56^\circ$  for the last screw) and planned further cadaver testing. In addition, Kostrezwski *et al.* measured the average time needed to use their system and claimed that a conventional image-guided procedure was only 3 min shorter, a negligible difference for an intervention lasting several hours.

#### RIME

Boschetti *et al.* (27) in 2005 proposed the robot in medical environment (RIME) project, a robotic system designed for drilling in transpedicular fixation surgeries. The project's main contributions were development of a fully teleoperated system, which permitted the surgeon to operate on a patient who could be kilometres away, and haptic feedback, provided to the surgeon using the custom PiRoGa5 device. Experiments reported in 2007 by Rosati *et al.* (28) demonstrated the feasibility of haptic feedback transmission and control of a six-DoF industrial robot between two cities separated by 35 km, although the authors still needed to integrate the optical tracking device proposed by Boschetti *et al.* into the whole system. No publications about experiments with cadavers or animals were found at the time of writing of this study.

#### RSSS

Jin *et al.* (29) have recently proposed a new surgical robot for pedicle screw insertion, named the robot spinal surgical system (RSSS), based on a five-DoF SCARA robot equipped with an infrared tracking device. RSSS's mechanical design ensures that the robot should not collapse under its own weight in the case of a power failure, ensuring the patient's safety. RSSS offers haptic feedback, virtual fixtures, a screw-implanting mechanism and a control strategy for automated drilling, which is able to identify the force profiles for each drilling stage and automatically stop before breaching the vertebra (30). Currently, this project is at an experimental stage and only experiments for the tuning of control parameters have been reported.

### Robot for laminectomy

In 2010, Wang *et al.* (31) proposed a robot for laminectomy, i.e. removal of posterior bony sections of vertebrae to alleviate nerve compression produced by diseases such as stenosis. This type of procedure requires milling of bone in the vicinity of the spinal cord; thus, a high level of precision is required, as damage to the latter must be prevented at all costs. The authors proposed a robot with two translational DoFs capable of automatic machining of the lamina and able to stop just before penetration into the spinal canal, leaving a thin layer of bone which could be later removed by the surgeon. The robot was equipped with force sensors and custom algorithms able to identify the bone layer being machined, according to the measured force profiles. The authors reported experimental results on 10 bovine spine samples, in which they measured the thickness of the bone layer left by the robot, which had an average value of 1.1 mm. No breaching into the spinal canal was observed and the robot's recorded working times were 10–14 min,

similar to times taken by surgeons doing the same task. Further work was planned by the authors to build a more stable mounting platform for the robot, as well as additional experiments.

## Robots for needle-based interventions

A considerable number of recent robotics projects (5 of 18) have addressed needle-based interventions, such as biopsies and vertebroplasties. As it will be seen, many of these were not specifically designed for use on the spine, as needle-based interventions can be executed in many other anatomical regions. A summary of the most relevant experiments using these robots is given in Table 3 and detailed descriptions are given in the sections below.

### AcuBot

One year before publication of the MARS robot, Cleary *et al.* (32) presented a plan for development of a minimally invasive system for spinal surgery. In this article, the authors identified multiple technical problems found in the implementation of a system of this kind: unavailability of intra-operative axial images, difficult fusion of CT and MR data, lack of visualization of oblique trajectories, unavailability of spinal tracking systems, slow and difficult instrument insertion and lack of appropriate software. The authors, to solve the aforementioned problems, advocated the use of intra-operative CT, 3D visualization, optical tracking systems, robotic tool holders and development of specialized software. This technical plan led to the development in 2003 of the AcuBot, a robot designed for percutaneous needle insertion guided by fluoroscopy, using one or two planes, or intra-operative CT scans (1). AcuBot received clearance from the FDA and clinical trials with 20 patients who underwent spinal nerve blockade were published in 2005 (5).

Acubot, shown in Figure 7, had a total of six DoFs, decoupled in positioning, rotation and instrument insertion. A three-DoF Cartesian manipulator, mounted on a bridge attached to the scanner's table, supported a remote centre of motion (RCM) mechanism with two DoFs, with the instrument mounted on its end-effector, which had an additional translational DoF along the instrument axis. Normally, the Cartesian manipulator brought the needle close to the insertion point, the RCM corrected its orientation and, after approval of the surgeon, the instrument was inserted to reach the target point inside the patient's body. In addition, a seven-DoF passive mechanism was mounted between the Cartesian manipulator and the

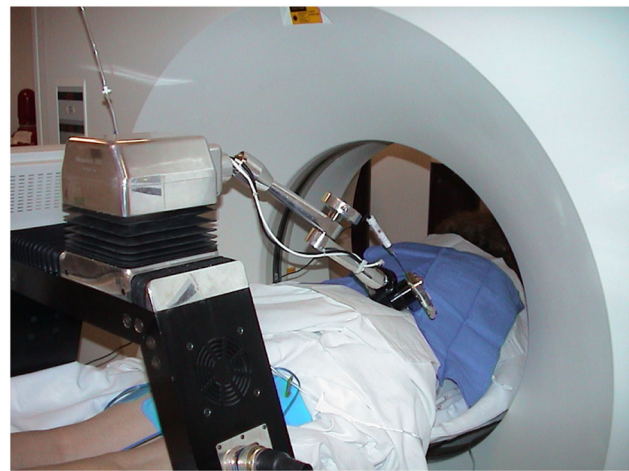


Figure 7. AcuBot being used in a CT-guided needle insertion: the three DoF Cartesian manipulator is placed over the black bridge attached to the scanner's table; the RCM and the linear end-effector are placed at the end of the passive articulated arm, which comes out from the right side of the Cartesian mechanism. Reprinted with permission from URobotics Lab, Johns Hopkins University. Copyright © 2012 URobotics Laboratory, Johns Hopkins University

Table 3. Brief description of reported experiments for robots designed for needle insertion tasks

Robot	Brief description	Evaluation criteria	Results	Reference
Acubot	Randomized clinical trial with 20 patients, of which 10 were operated with the robot and 10 using a conventional manual technique	Measurement of needle deviation from the planned target point using biplanar fluoroscopy	Mean deviation with robot, 1.105 mm; mean deviation with manual technique, 1.238 mm	(5)
Innomotion	Testing of robot-guided percutaneous needle insertions on four pigs put under general anaesthesia	Target deviation measured using MRI	Axial deviation in the $\pm 1$ mm range (min, 0.5 mm; max, 3 mm). Transverse angular deviation in the $\pm 1^\circ$ range (min, $0.5^\circ$ ; max, $3^\circ$ )	(2)
Innomotion	25 MR-guided punctures on phantoms placed within water-filled containers	Deviations from planned target points measured by hand, using rulers	Observed deviation of $2.2 \pm 0.7$ mm	(35)
DLR LWR III (Onogi <i>et al.</i> )	<i>In vitro</i> mechanical trials using a precisely constructed phantom <i>In vitro</i> test of 50 punctures on the pedicles of five spinal phantoms	Deviation measured from post-operative 3D radiographies Deviation measured with post-operative CT scans	$1.2 \pm 0.4$ mm (max, 1.98 mm) Translational deviation: $1.46 \pm 0.80$ mm; angular deviation, $1.49 \pm 0.64^\circ$	(3) (36)
SpineNav	<i>In vitro</i> mechanical trials, measuring errors in 30 positions within the robot's workspace	Deviation measured using a 3D digitizing arm	$0.89$ mm (max, 1.14 mm)	(38)

RCM mechanism, which was manually adjusted by the surgeon before the procedure, bringing the instrument close to the entry points. The AcuBot also included a display and a joystick, used by the surgeon to control the robot remotely.

A clinical trial was reported by Cleary *et al.*, in which the AcuBot was used to perform biplanar fluoroscopy-guided nerve and facet blocks (5). This type of procedure consists of the localization of the source of back pain by insertion of 22-gauge needles in precise locations of the spine, followed by injection of local anaesthetics. In the reported trial, a randomized study was performed at the Georgetown University Medical Centre with 20 patients, 10 of which underwent the conventional procedure and the remaining 10 were operated using the AcuBot. Needle insertion accuracy and pain relief were measured for both groups of patients and the results were similar for both measures. Mean deviations for the robot and manual methods were 1.105 and 1.238 mm, respectively. Pain scores, measured in the range 0–10, were reduced from 6.3 to 1.8 using the robot and from 6.0 to 0.9 using the manual method. Although the results give the impression that the AcuBot is as accurate and effective as the manual method, the authors acknowledged that the statistical sample was too small to draw significant conclusions. Currently, research with the AcuBot is focused on development of a rotating needle holder for improved lesion targeting in soft organs, such as the liver and lung, giving less attention to spinal procedures (33).

#### Innomotion

MR offers interesting advantages for robotic and image-guided surgery, as it offers superior soft tissue contrast and does not irradiate the patient. However, the strong magnetic fields present in all MR systems greatly complicate the robotic design, as compatible materials, sensors and actuators must be used. In addition, an MR-compatible robot should have a reduced size to fit into the small space of the magnet's bore, largely occupied by the patient. All of these factors make development of MR-compatible robots a formidable challenge. A remarkable example, used in spinal procedures, is the work by Hempel *et al.* (34), who in 2003 presented the manipulator for interventional radiology (MIRA), which evolved into the Innomotion system (2). The latter obtained CE clearance and was introduced to the market by Innomedic GmbH (Herxheim, Germany), which was acquired by Synthes (Solothurn, Switzerland) in 2008. The Innomotion's commercialization was stopped in early 2010 and is expected to be restarted in 2012 by the IBSmm Company (Brno, Czech Republic), which is now working on the robot's improvement.

Innomotion, shown in Figure 8, was designed as a tele-manipulator for MR-guided insertion of cannulae and probes for biopsy, drainage, drug delivery and energetic tumour destruction. Although direct interventions in the central nervous system were left out, due to the demanding regulations and long approval process, Innomotion can still be used for interventions in the spine's periphery. The robot's kinematics consists of an arm driven in five DoFs,



Figure 8. Innomotion robot, used for CT- and MR-guided needle-based procedures. Reprinted with permission from Innomedic GmbH. Copyright © Innomedic GmbH

attached to an orbiting ring mounted on the scanner's table, and is equipped with linear pneumatic actuators and optical limit switches, rotational and linear encoders. Innomotion's instrument holder was designed as a RCM with two DoFs and was equipped with gadolinium-filled spheres, which could be easily segmented from intra-operative MR images to detect its position and orientation.

Melzer *et al.* (2) published the results of animal tests in which the robot's deviation in the axial plane was estimated to be within the  $\pm 1$  mm range (minimum, 0.5 mm; maximum, 3 mm) and its angular deviation to be  $1^\circ$  (minimum,  $0.5^\circ$ ; maximum,  $3^\circ$ ). These results were compliant with the CE standard, although they were not sufficient for interventions in the central nervous system (2). In 2010, Moche *et al.* (35) published a study with accuracy measurements of Innomotion, using phantoms as well as clinical trials. In the phantom study, 25 needle insertions were performed, with observed deviation between the target and observed points of  $2.2 \pm 0.7$  mm, measured by hand using rulers. The reported clinical trials consisted of diagnostic biopsies which required planning and execution times of 25 and 44 min, respectively. Of the six reported interventions, two were carried out successfully around the spine: one was a bone biopsy in the iliac crest and one was an abscess aspiration in the L5–S1 region. No complications were observed in all six cases.

#### DLR's LWR III

A following version of DLR's LWR, the LWR III, is now commercialized by KUKA and is increasingly being adopted for surgical robotics projects, such as the one designed for spine biopsies and vertebroplasties presented by Tovar-Arriaga *et al.* (3). This project consisted of the aforementioned robot guided by intra-operative 3D radiographies, acquired by a rotational C-arm, and an optical infra-red tracking system. The authors reported two experiments. In the first, they measured the errors of calibration between the tooltip positions measured by the optical system and the robot's

controller, which had a mean of 0.23 mm, a deviation of 0.1 mm and a maximum value of 0.47 mm. In the second experiment, the authors positioned the tooltip in various locations over a precisely manufactured phantom and measured the deviations with 3D radiographies; the authors estimated the error to be in the  $1.2 \pm 0.4$  mm range, with minimum and maximum values of 0.3 and 1.98 mm, respectively. Overall, the reported accuracies were acceptable for the demands of surgery, although the authors cited the optical system's accuracy and low sampling rate (20 Hz) as limiting factors that should be improved in future versions.

#### *University of Tokyo's robot for vertebroplasty*

A group of Japanese researchers from the cities of Tokyo and Osaka presented a robotic system for vertebroplasty, based on a robot with a compact end-effector, which could be inserted in the space between the C-arm and the patient. Surgical planning was carried out on pre-operative CT scans, whilst intra-operative guidance relied on fluoroscopy. For this purpose, the needle holder was built with plastic material to make it partially radiolucent. In addition, this mechanical device could be automatically detached from the robot by a safety mechanism, triggered when excessive forces were applied to the needle (4). In 2009, Onogi *et al.* (36) reported an *in vitro* experiment in which the robot was used for 50 punctures in the pedicles of five polyurethane phantoms of lumbar spines. Deviation, measured from post-operative CT scans, was estimated to be  $1.46 \pm 0.80$  mm and  $1.49 \pm 0.64^\circ$  (36).

#### *SpineNav*

In 2008, Ju *et al.* (37) presented the SpineNav, a robot for percutaneous vertebroplasty which could insert needles autonomously or using a tele-operated mechanism with five DoFs. This robot was designed to be used inside a CT scanner and its mounting platform has a metal mask which can be easily segmented from the intra-operative images to estimate the robot's base position and orientation with respect to the patient. Accuracy tests carried out by the authors estimate SpineNav's mean positioning error as 0.89 mm, with a maximum of 1.14 mm (38). To date, no reports about experiments with cadavers or clinical trials using SpineNav are available.

## **Robots for endoscopic interventions**

#### *MINOSC – sub-arachnoid space exploration*

The microneuro-endoscopy of spinal cord (MINOSC) European project led to the development of a robotic system for interventions of the spinal cord from within the sub-arachnoid space. This is a challenging task, as this section of the spine is only a few millimetres wide and is surrounded by delicate structures which can easily become damaged. Ascari *et al.* (9) published results of the design of a robot-assisted endoscope, which provides the surgeon with direct vision of the surrounding structures – spinal cord, blood vessels and nerve roots – and permits operations such as localized electro-stimulation.

The system uses image-processing techniques to analyse its surroundings and give feedback to its control unit, which can steer the endoscope tip to avoid obstacles which may not even be present in the endoscope's field of view. Steering is implemented by a two-DoF cable-driven mechanism and three lateral hydraulic jets that stabilize the endoscope's tip.

In 2010, Ascari *et al.* (9) reported a series of *in vitro*, *ex vivo* and *in vivo* experiments, which validated all the prototype's subsystems, excluding navigation, which was tested up to *in vitro* experiments. In addition, localized electrostimulation of nerve roots was successfully accomplished in an additional *in vivo* test. According to the authors, the prototype is still far from reaching clinical use, but the major implementation problems were already solved in its current stage.

#### *da Vinci*

The da Vinci surgical robot (Intuitive Surgical, Sunnyvale, CA, USA), mostly used in urological and gynaecological surgeries, has also been tested for endoscopic spinal interventions, although its applications are limited. In fact, the da Vinci's end-effectors are not well suited for bone drilling, due to the limited range of force they offer, as they were designed primarily for the manipulation of soft tissue (39). However, there are reports of successful experiments using it for spinal interventions, although all are at an early experimental stage.

Yang *et al.* (7) published a review of experimental uses of the da Vinci on spinal procedures, along with a report of five successful cases of paravertebral tumour resections. Lee *et al.* (40) published a study on two cadavers, which demonstrated the feasibility of using the da Vinci for transoral decompression of the cranio-cervical junction, and Ponnusamy *et al.* (41) reported successful laminotomy, laminectomy, disc incision and dural-suturing procedures on a pig, using a posterior approach. The lack of appropriate tools for the da Vinci is repeatedly cited as a problem, although Ponnusamy *et al.* reported the use of a prototype burr, rongeur and laser instrument, the last one used for rapid coagulation.

Kim *et al.* (42) reported an experiment on anterior lumbar interbody fusion (ALIF) using the da Vinci on a pig, inserting a metal cage in the inter-disc space. Although ALIF was proposed several years ago, post-operative complications have prevented its widespread use. The work of Kim *et al.* (42) expects to increase this surgery's safety by incorporating robotic assistance, although it is still at an early stage.

## **Radiosurgery robotic systems**

Current radiosurgical systems employ heavy-duty robots to move a linear accelerator (LINAC) around the patient, firing high-energy beams according to a predefined plan, ablating internal tumours and minimizing damage to surrounding healthy tissue. Although radiosurgical systems do not come into contact – or even near – the patient, we

considered that they should be included in this review, as they are currently used for the treatment of spinal lesions and they fit the criteria set out in Methods, as they autonomously perform a clearly defined surgical task with direct impact on the patient's body.

Radiosurgery was conceived as a treatment for deep-seated intracranial tumours, for which conventional surgery is considered too dangerous or infeasible. The first commercially available radiosurgical system was the GammaKnife (Elekta AB, Stockholm, Sweden), which was introduced to the market in 1968, and since then, radiosurgery has gained worldwide acceptance and is now considered within standard oncological practice. Nowadays, the market is dominated by the CyberKnife (Accuray Inc., Sunnyvale, CA, USA) and the Novalis (BrainLAB, Heimstetten, Germany), which permit interventions guided by intra-operative imaging without the need of stereotactical frames. Using this, a pair of X-ray devices acquires images of the patient at regular intervals, which are processed to monitor the patient's position and adjust the LINAC accordingly, minimizing deviations from the surgical plan.

Nowadays, radiosurgery is used for the treatment of lesions found in many extracranial regions, including the spine. A recent review by Romanelli and Adler (6) cites multiple clinical studies of spinal radiosurgery, stating that this technique is well suited for treatment of neoplastic lesions and intramedullary arteriovenous malformations. In addition, spinal radiosurgery offers an effective and well-tolerated option, as suggested by a study made in Pittsburgh, which followed 393 patients and observed high rates of long-term pain control (86%) and long-term tumour control (88%), with no cases of neurological damage induced by radiation (43). Radiosurgery was not considered practical before the introduction of image guidance, as the first reported cases used a stereotactic frame which had to be attached to the spinous processes of the vertebrae, previously exposed by multiple incisions. This was naturally too cumbersome and not usable in treatments that required multiple radiation doses distributed along multiple sessions (44). The introduction of frameless image-guidance permitted more practical uses in spinal surgery, although the first reported studies still relied on fiducial markers inserted into the vertebrae adjacent to the lesion. Further development of image-guidance technology permitted interventions without the need of any type of marker and without noticeable reductions in accuracy: studies estimate that fiducial-based spinal radiosurgery is accurate to within a mean distance of 0.7 mm (45) and image-based is accurate to a mean distance of 0.5–0.6 mm (46,47).

Accuray and BrainLAB host extensive lists of publications related to the CyberKnife<sup>5</sup> and Novalis<sup>6</sup> systems on their respective websites. Interested readers should consult them for additional information.

<sup>5</sup><http://www accuray.com/healthcare-professionals/clinical-publications/cyberknife-publications#spine>

<sup>6</sup>[http://www.novalis-radiosurgery.com/wp-content/uploads/2009/07/NTx+NV\\_Biblio\\_DEC0709\\_SPINE.pdf](http://www.novalis-radiosurgery.com/wp-content/uploads/2009/07/NTx+NV_Biblio_DEC0709_SPINE.pdf)

## Discussion

### Robot design and safety

In the early days of surgical robotics, researchers adapted industrial robots for use in the operating room but, in the last decade, there is a clear tendency in favour of specifically designed ones. Spinal surgery has been no exception. In the early years, 1992–2002, researchers such as Sautot *et al.* (10) and Santos-Munné *et al.* (11) adapted industrial robots for surgical use. In the last decade, we have seen the appearance of robots specialized for surgical applications. Remarkable examples are SpineAssist (14), AcuBot (1), Innomotion (2), the SPINEBOT series (21,23), CoRA (22) and the DLR's LWR series (3,24). More recent studies continue in the same line, proposing new models rather than adapting industrial robots. Examples are SpineNav (37), RSSS (29) and the studies by Onogi *et al.* (4). This shift has been caused by safety requirements: industrial robots are designed to perform tasks – usually involving high torque or speed – in the absence of humans, whereas surgical robots must constantly interact with the surgeon, clinical staff and the patient (who is absolutely unable to react in case of emergency). Besides, it must be possible to make them sterile, using draping to reduce the risk of infection. It is noteworthy that, as medical robots are relatively new, no international standards yet exist for them, although the International Standardization Organisation (ISO) and the International Electrotechnical Commission (IEC) are currently working on their development.

There is also a tendency to increase safety by giving less autonomy to robots in the operating room. In fact, surgeons seem to prefer to be in control of all the intervention's tasks, restricting the use of robots for assistance. This approach is desirable, as it combines the strengths of robots (stability, precision and immunity to fatigue) and humans (better analysis, judgement and response in unexpected situations), who work cooperatively and increase the surgery's safety. A remarkable example is the SPINEBOT series: its first prototype had automated motion and drilling (21), but these features were not present in the second model. In fact, SPINEBOT v 2's main capability was keeping the instrument in a stable position, leaving gross positioning and drilling in hands of the surgeon (23).

### Accuracy

A summary of accuracy experiments for robots designed for screw insertion is given in Table 2, which shows that many are capable of inserting screws with > 85% possibility of success and a deviation of 1–2 mm. Of particular interest is the retrospective clinical study by Devito *et al.* (19), which analysed 646 insertions performed using SpineAssist and concluded that 635 (98.3%) were inserted with errors < 2 mm. Table 3 also shows a summary of experiments, but only for robots designed for needle-based procedures. The table's data shows that these robots are also capable of precise insertions with errors bounded by the same

values. It can be concluded that current robotic technology is capable of accurate instrument placement in the 1–2 mm range, but not yet able to reach sub-millimetre accuracy in realistic conditions (i.e. in actual interventions or *in vivo* experiments). In the current situation, we could say that robots are faced with a '1 mm barrier', which they have not yet been able to overcome. Going below this limit has clinical relevance, as pointed out by Rampersaud *et al.* (48), who estimated that 1 mm and 5° were the maximum translational and rotational errors that could be admitted in screw insertion in the mid-cervical spine, the mid-thoracic spine and the thoracolumbar junction. Among the factors that influence this, we can cite imaging system resolution, registration inaccuracies and the motion of vertebrae. Robots for screw insertion are also affected by drill slippage, vibrations and reactive forces, whereas the main sources of error for needle-based ones are needle deflection and tissue deformation.

## Registration and tracking technologies

In terms of tracking and registration technology, projects designed for screw insertion have preferred optical tracking, with the remarkable exceptions of SpineAssist and SPINEBOT v 2. Robots for biopsies and other needle-based procedures prefer less invasive tracking technologies, such as fluoroscopy and intra-operative CT, which prevent unnecessary incisions. Today, all available technologies for tracking and registration have inconveniences. On the one hand, optical tracking offers sub-millimetre precision at a reasonable cost and can reduce the required number of X-rays, as periodic imaging to locate the surgical tools becomes less necessary. However, optical tracking suffers from marker occlusions and low sampling rates – something which has been repeatedly cited as a problem (3,25) – and mounting of markers requires rigid attachment to the patient's bony structures, which translates into more incisions and higher invasiveness. On the other hand, fluoroscopy and intra-operative CT are less invasive, but their use exposes the patient, surgeon and clinical staff to higher doses of radiation, which is undesirable. Intra-operative MR is not well suited for spinal surgery, as bone is not visible on MR images, as it produces no signal. Besides, it is still uncommon in most hospitals and its strong magnetic field mandates the replacement of all surgical tools and implants by their MR-compatible versions.

Patient registration has the additional problem of the relative motion of the vertebrae. If a single vertebra is tracked, it is unrealistic to assume that the adjacent ones will move in the same manner or, in other words, to consider the spine as a rigid body. One option to solve this problem is reduction of the spine's range of motion by means of additional hardware, such as the SpineAssist's Hover-T. Another interesting approach is the one used by SPINEBOT v 2, which uses individual registration of vertebrae from biplanar fluoroscopic images updated in real time, which, obviously, has the inconvenience of higher radiation (23). The spine's relative motion cited

here and the tracking systems' trade-offs make the choice of a registration strategy a problem for which no obvious solution yet exists.

## Project development

Nowadays, Mazor Robotics' SpineAssist is the only commercially available robot – with FDA and CE clearances – specifically designed for spinal surgery, particularly transpedicular fixation. There are seven other projects for similar applications but, as far as we know, none of them have yet obtained any of the aforementioned clearances. The difficult and expensive certification procedures and the high cost of robotics projects *per se* are big hindrances for companies wishing to enter the medical robotics market. All this forms a scenario in which Mazor Robotics could remain without direct competitors for some time.

However, other commercial robots are now used for spinal surgery, although they, differing from SpineAssist, were not specifically designed for this application. In fact, CyberKnife and Novalis are used for spine-related procedures and the da Vinci has also been used for them, although the reported cases are still at experimental stages and its adoption in a clinical environment does not seem to happen soon.

## Economic analysis

To the best of our knowledge, there is no publication available which analyses the costs and benefits, from the clinical point of view, of robotics in spinal surgery. Even more, there are no studies today regarding the cost-effectiveness of image-guided spinal surgeries, according to Tjardes *et al.* (49). It is necessary for hospitals to ensure that the benefits brought by robotic surgery outweigh the costs, which are very high. As an example, installation of a Mazor Robotics' Renaissance system has a cost of \$789K (including the robot, workstation, instrument tray and 1 year of technical support), while each intervention requires disposable materials, which cost \$1.2K, and implants valued between \$6K and \$8K. In addition, technical support from Mazor must be renewed annually, signing contracts of 10% of the installation price per year (15).

## Conclusions

This article has reviewed the state of the art in surgical robotics for spinal interventions. Several prototypes and commercially available systems have been analysed, showing that this particular field is still at an early stage of development. Up to this date, only one robot specifically designed for spinal surgeries is available in the market – SpineAssist/Renaissance – while the others are research prototypes or commercial robots originally designed for other uses.

Among spine-specific applications, the most studied one has been screw insertion, for which current technology offers increased levels of safety, considerably reducing the number of misplaced screws. The accuracy of robots for this application, and also for needle insertion, permits instrument placements with deviations of 1–2 mm.

Robots not only make existing surgeries safer: they also enable surgeons to do interventions which, without their assistance, would be absolutely infeasible. Two remarkable examples are SpineAssist's GO-LIF (20) and the sub-arachnoid space exploration permitted by MINOSC (9). These projects are examples that robotic surgery can not only improve existing interventions, they can also be 'enabling' technology (20).

However, the field of robotics for spinal surgery still faces considerable challenges. Sub-millimetre precision in instrument placement, under realistic conditions, has not yet been achieved. Patient tracking and registration still have demanding problems, as no technology is capable of simultaneously offering high accuracy, low invasiveness, low radiation and high robustness. Also, the relative motion of vertebrae introduces an additional problem in registration, which still needs to be addressed properly. In economic terms, ingenious solutions are needed to bring down the cost of robotic systems. The latter is still high and has prevented a more widespread use of surgical robots, as hospitals are unsure whether their clinical benefits outweigh their elevated price. All these present challenges show that spinal surgical robotics still has potential that can be transformed into increased patient well-being.

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## Conflict of Interest

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

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